Strangeness in the proton and $N^*(1535)$

B.S.Zou[a]

[a]Institute of High Energy Physics, CAS, P.O.Box 918(4), Beijing 100049, China

The newest progress on the study of the strangeness in the proton and in the lowest negative parity nucleon excited state $N^*(1535)$ is reviewed. Implications on the internal quark structure of the proton, $N^*(1535)$ and other baryons are discussed. The diquark cluster picture for the 5-quark components in baryons gives a natural explanation not only to the empirical indications for a positive strangeness magnetic moment μ_s and positive strangeness radius of the proton but also the longstanding mass-reverse problem of $N^*(1535)$, $N^*(1440)$ and $\Lambda^*(1405)$ resonances as well as the unusual decay pattern of the $N^*(1535)$ resonance. Evidence for possible existence of $N^*(1535)$'s $1/2^-$ SU(3) nonet partners in this picture is pointed out, and suggestion is made to search for these $1/2^-$ hyperon excited states under the well known $\Sigma^*(1385)$, $\Lambda^*(1520)$ and $\Xi^*(1530)$ peaks in various reactions.

1. Introduction

In classical quark models, each baryon is composed of three quarks. The simple 3q constituent quark model has been very successful in explaining the static properties, such as mass and magnetic moment, of the spatial ground states of the flavor SU(3) octet and decuplet baryons. Its predicted Ω baryon with mass around 1670 MeV was discovered by later experiments.

However its predictions for the spatial excited baryons failed badly. In the simple 3q constituent quark model, the lowest spatial excited baryon is expected to be a (uud) N^* state with one quark in orbital angular momentum $L = 1$ state, and hence should have negative parity. Experimentally [1], the lowest negative parity N^* resonance is found to be $N^*(1535)$, which is heavier than two other spatial excited baryons : $\Lambda^*(1405)$ and $N^*(1440)$. In the classical 3q constituent quark model, the $\Lambda^*(1405)$ with spin-parity $1/2^-$ is supposed to be a (uds) baryon with one quark in orbital angular momentum $L = 1$ state and about 130 MeV heavier than its N^* partner $N^*(1535)$; the $N^*(1440)$ with spin-parity $1/2^+$ is supposed to be a (uud) state with one quark in radial $n = 1$ excited state and should be heavier than the $L = 1$ excited (uud) state $N^*(1535)$, noting the fact that for a simple harmonic oscillator potential the state energy is $(2n + L + 3/2)\hbar\omega$. So for these three lowest spatial excited baryons, the classical quark model picture is already failed.

The second outstanding problem in the classical quark model is that it predicts a substantial number of 'missing N^* states' around 2 GeV/c^2, which have not so far been observed [2]. The third outstanding problem is that from deep inelastic scattering and Drell-Yan experiments the number of $\bar{d}$ is found to be more than the number of $\bar{u}$ by 0.12

in the proton [3].

The failure of the classical quark models raises a fundamental question : what are effective degrees of freedom for describing the internal structure of baryons? Several pictures based on various effective degrees of freedom have then been proposed, such as quark-gluon hybrid model, diquark model, meson-baryon state, pentaquark with diquark clusters as shown in Fig.1.

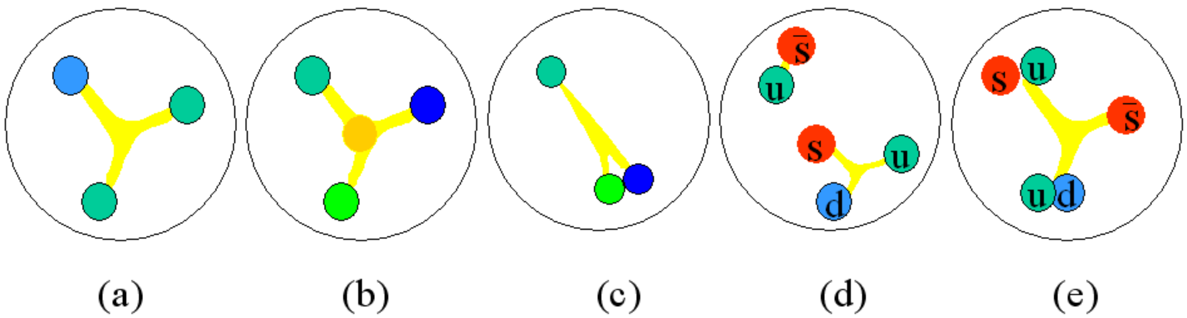

Figure 1. Various pictures for internal quark-gluon structure of baryons: (a) $3q$, (b) $3qg$ hybrid, (c) diquark, (d) meson-baryon state, (e) pentaquark with diquark clusters.

Among various pictures for the baryon, the meson cloud picture seems quite successful. With this picture, the excess of $\bar{d}$ over $\bar{u}$ in the proton is explained by a mixture of $n\pi^+$ with the π^+ composed of $u\bar{d}$ [4]; the $N^*(1535)$ and $\Lambda^*(1405)$ are ascribed as quasi-bound states of $K\Sigma$ and $\bar{K}N$, respectively [5].

To understand 5-quark components in baryons, to study the strangeness in the proton and in the lowest negative parity nucleon excited state $N^*(1535)$ should be very instructive. In the following, by studying the strangeness in the proton and $N^*(1535)$, we will show that instead of the conventional "meson cloud" configurations the diquark-diquark-antiquark configurations could play very important or even dominant role in excited baryons.

2. Strangeness in the proton

There has long been some evidence that there may be $\bar{s}s$ pairs in the nucleon [6]. Several measurements including the πN σ-term, neutrino-induced charm production and polarization effects in electron-nucleon deep-inelastic scattering indicate that there may be significant $s\bar{s}$ component in the proton [6, 7, 8]. The excesses of ϕ production in $\bar{p}p$ annihilation [9] above the naive OZI rule predictions were also used to argue in favor of a significant $\bar{s}s$ component in the proton [10] although the results can also be explained by two-step contribution [11] without introducing explicitly the $\bar{s}s$ component in the proton.

For the strangeness in the proton, an interesting issue is whether the s and $\bar{s}$ distributions are the same ? In the meson-cloud picture with a mixture of $K^+\Lambda$ component in the proton, s-$\bar{s}$ asymmetry is naturally expected. The strangeness spin Δ_s, strangeness magnetic moment μ_s and strangeness radius r_s are all predicted to be negative [14, 15].

There are some empirical indications for a negative Δ_s value as (-0.10 ± 0.06) [12, 13], which is compatible with the expectation from the simple meson-cloud model.

For the strangeness magnetic moment μ_s and strangeness radius, there are many other model predictions, such as including $K^*\Lambda$ meson-cloud contribution which may change the sign of the μ_s by adjusting model parameters [16].

However, recently four experiments on parity violation in electron-proton scattering suggest that both strangeness magnetic moment μ_s and strangeness radius r_s of the proton are positive [17]. This is in contradiction with most theoretical calculations [18, 19].

A complete analysis [18] of the relation between these strangeness observables and the possible configurations of the $uuds\bar{s}$ component of the proton concludes that, for a negative Δ_s, positive μ_s and r_s, the $\bar{s}$ is in the ground state and the $uuds$ system in the P-state. The conventional $K^+\Lambda$ configuration as shown in Fig. 1(d) has the $\bar{s}$ mainly in P-state and hence leads to negative value for both μ_s and r_s. The hidden strangeness analogues of recently proposed diquark cluster models [20] for the θ^+ pentaquark as shown in Fig. 1(e) have $\bar{s}$ in the ground state and the $uuds$ system in the P-state, hence give positive value for both μ_s and r_s. The diquark cluster configurations also give a natural explanation for the excess of $\bar{d}$ over $\bar{u}$ in the proton with a mixture of $[ud][ud]\bar{d}$ component in the proton.

Some recent theoretical attempts with closer relation to QCD [21, 22] have not given a conclusive view on the sign of the μ_s. A very recent analysis [23] of combined set of parity-violating electron scattering data gives the strange form factors to be consistent with zero. If the result be further proved by more precise measurements and analyses in the furure, it could mean that there may be about equal amount of meson-cloud components and $q^2q^2\bar{q}$ components in the proton.

3. Strangeness in $N^*(1535)$ and implication on its $1/2^-$ SU(3) nonet partners

From the study of the proton, we know that there should be at least about 20% mixture of the penta-quark components in the proton to reproduce its large $\bar{u}$-$\bar{d}$ asymmetry ($\bar{d}-\bar{u} \approx 0.12$) and s-$\bar{s}$ asymmetry. Then in the excited nucleon states, N^* resonances, more multi-quark components should be expected. To understand the properties of the N^* resonances, it is absolutely necessary to consider these multi-quark components.

Recently BES experiment at Beijing Electron-Positron Collider (BEPC) has been producing very useful information on N^* resonances [24, 25, 26]. From BES results on $J/\psi \to \bar{p}p\eta$ [24] and $\psi \to \bar{p}K^+\Lambda$ [25], the ratio between effective coupling constants of $N^*(1535)$ to $K\Lambda$ and $p\eta$ is deduced to be $g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta} = 1.3 \pm 0.3$ [27]. With previous known value of $g_{N^*(1535)p\eta}$, the obtained new value of $g_{N^*(1535)K\Lambda}$ is shown to reproduce recent $pp \to pK^+\Lambda$ near-threshold cross section data as well. Taking into account this large $N^*K\Lambda$ coupling in the coupled channel Breit-Wigner formula for the $N^*(1535)$, its Breit-Wigner mass is found to be around 1400 MeV, much smaller than previous value of about 1535 MeV obtained without including its coupling to $K\Lambda$.

The nearly degenerate mass for the $N^*(1535)$ and the $N^*(1440)$ resonances can be easily understood by considering 5-quark components in them [27, 28, 29]. The $N^*(1535)1/2^-$ could be the lowest $L = 1$ orbital excited $|uud>$ state with a large admixture of $|[ud][us]\bar{s}>$ pentaquark component having $[ud]$, $[us]$ and $\bar{s}$ in the ground state. Note

that the N^* with negative parity cannot have $|[ud][ud]\bar{d}>$ component with two identical diquarks. The $N^*(1440)$ could be the lowest radial excited $|uud>$ state with a large admixture of $|[ud][ud]\bar{d}>$ pentaquark component having two $[ud]$ diquarks in the relative P-wave. While the lowest $L = 1$ orbital excited $|uud>$ state should have a mass lower than the lowest radial excited $|uud>$ state, the $|[ud][us]\bar{s}>$ pentaquark component has a higher mass than $|[ud][ud]\bar{d}>$ pentaquark component. The large mixture of the $|[ud][us]\bar{s}>$ pentaquark component in the $N^*(1535)$ may also explain naturally its large couplings to the $N\eta$ and $N\Lambda$ meanwhile small couplings to the $N\pi$ and $K\Sigma$. In the decay of the $|[ud][us]\bar{s}>$ pentaquark component, the $[ud]$ diquark with isospin $I = 0$ is stable and keeps unchanged while the $[us]$ diquark is broken to combine with the $\bar{s}$ to form either $K^+(u\bar{s})\Lambda([ud]s)$ or $\eta(s\bar{s})p([ud]u)$.

The lighter $\Lambda^*(1405)1/2^-$ is also understandable in this picture. Its dominant 5-quark configuration is $|[ud][us]\bar{u}>$ which is lighter than the corresponding 5-quark configuration $|[ud][us]\bar{s}>$ in the $N^*(1535)1/2^-$.

From above results, we see that the diquark cluster picture for the 5-quark components in baryons also gives a natural explanation to the longstanding mass-reverse problem of $N^*(1535)$, $N^*(1440)$ and $\Lambda^*(1405)$ resonances as well as the unusual decay pattern of the $N^*(1535)$ resonance. However, if this picture is correct, there should also exist the SU(3) partners of the $N^*(1535)$ and $\Lambda^*(1405)$, *i.e.*, an additional Λ^* $1/2^-$ around 1570 MeV, a triplet Σ^* $1/2^-$ around 1360 MeV and a doublet Ξ^* $1/2^-$ around 1520 MeV [28]. There is no hint for these baryon resonances in the PDG tables [1]. Where are they? Here I want to point out that there is indeed evidence for all of them in the data of J/ψ decays at BES.

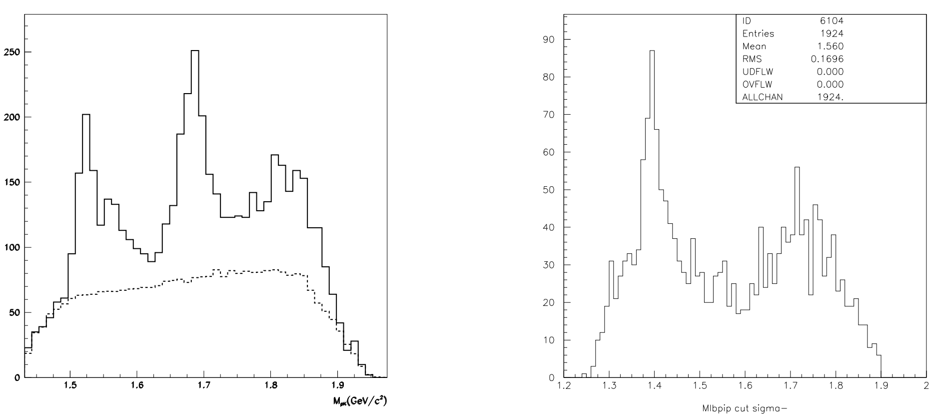

Figure 2. pK invariant mass spectrum (left) for $J/\psi \to pK^-\bar{\Lambda}$+c.c. and $\Lambda\pi$ invariant mass spectrum (right) for $J/\psi \to \Lambda\bar{\Sigma}^+\pi^-$ from BES [30]

Fig. 2 shows the pK invariant mass spectrum (left) for $J/\psi \to pK^-\bar{\Lambda}$+c.c. and $\Lambda\pi$ invariant mass spectrum (right) for $J/\psi \to \Lambda\bar{\Sigma}^+\pi^-$ from BES [30]. In the pK invariant mass spectrum, under the narrow $\Lambda^*(1520)$ $3/2^-$ peak, there is a quite obvious broader peak around 1570 MeV. Preliminary partial wave analysis [31] gave its spin-parity as $1/2^-$. This $\Lambda^*(1570)$ $1/2^-$ resonance fits in the new scheme for the $1/2^-$ SU(3) baryon

nonet very well. In the $\Lambda\pi$ invariant mass spectrum, under the $\Sigma^*(1385)\ 3/2^+$ peak, there is also a broader peak around 1360 MeV. No partial wave analysis has been performed for this channel yet. But there is a good reason to reckon that there may be $1/2^-$ component underneath the $\Sigma^*(1385)\ 3/2^+$ peak.

According to PDG [1], the branching ratios for $J/\psi \to \bar{\Sigma}^-\Sigma^*(1385)^+$ and $J/\psi \to \bar{\Xi}^+\Xi^*(1530)^-$ are $(3.1\pm0.5)\times10^{-4}$ and $(5.9\pm1.5)\times10^{-4}$, respectively. These two processes are SU(3) breaking decays since Σ and Ξ belong to SU(3) $1/2^+$ octet while $\Sigma^*(1385)$ and $\Xi^*(1530)$ belong to SU(3) $3/2^+$ decuplet. Comparing with the similar SU(3) breaking decay $J/\psi \to \bar{p}\Delta^+$ with branching ratio of less than 1×10^{-4} and the SU(3) conserved decay $J/\psi \to \bar{p}N^*(1535)^+$ with branching ratio of $(10\pm3)\times10^{-4}$, the branching ratios for $J/\psi \to \bar{\Sigma}^-\Sigma^*(1385)^+$ and $J/\psi \to \bar{\Xi}^+\Xi^*(1530)^-$ are puzzling too high. A possible explanation for this puzzling phenomena is that there were substantial components of $1/2^-$ under the $3/2^+$ peaks but the two branching ratios were obtained by assuming pure $3/2^+$ contribution. This possibility should be easily checked with the high statistics BESIII data in near future.

4. Summary

The empirical indications for a positive strangeness magnetic moment and positive strangeness radius of the proton suggest that the 5-quark components in baryons may be mainly in colored diquark cluster configurations rather than in “meson cloud” configurations or in the form of a sea of quark-antiquark pairs. The diquark cluster picture also gives a natural explanation for the excess of $\bar{d}$ over $\bar{u}$ in the proton with a mixture of $[ud][ud]\bar{d}$ component in the proton. More precise measurements and analyses of the strange form factors are needed to examine the relative importance of the meson-cloud components and $q^2q^2\bar{q}$ components in the proton.

For excited baryons, the excitation energy for a spatial excitation could be larger than to drag out a $q\bar{q}$ pair from gluon field with the q to form diquark cluster with a valence quark. Hence the 5-quark components could be dominant for some excited baryons.

The diquark cluster picture for the 5-quark components in baryons also gives a natural explanation for the longstanding mass-reverse problem of $N^*(1535)$, $N^*(1440)$ and $\Lambda^*(1405)$ resonances as well as the unusual decay pattern of the $N^*(1535)$ resonance with a large $|[ud][us]\bar{u}>$ component.

The diquark cluster picture predicts the existence of the SU(3) partners of the $N^*(1535)$ and $\Lambda^*(1405)$, *i.e.*, an additional $\Lambda^*\ 1/2^-$ around 1570 MeV, a triplet $\Sigma^*\ 1/2^-$ around 1360 MeV and a doublet $\Xi^*\ 1/2^-$ around 1520 MeV [28]. There is evidence for all of them in the data of J/ψ decays at BES, which should be examined by high statistics data to be collected by BESIII in near future. One may also search for these $1/2^-$ hyperon excited states under the well known $\Sigma^*(1385)$, $\Lambda^*(1520)$ and $\Xi^*(1530)$ peaks in various other reactions, such as those at CEBAF and Sping-8.

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